SHRUB EXPANSION IN ARCTIC ALASKA: 50 YEARS OF CHANGE DOCUMENTED USING AERIAL PHOTOGRAPHY

By

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A

THESIS

Presented to the Faculty

of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

By

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Fairbanks, Alaska

December 2004

ABSTRACT

Evidence from arctic Alaska suggests that the terrestrial landscape is changing in response to warming. Between 1946 and 1951, several thousand low-altitude panchromatic oblique aerial photographs were taken as part of geologic reconnaissance and exploration of Alaska's Arctic Slope and Brooks Range. For this study, 202 of the landscapes in the old photographs were re-photographed. Comparison of the old and new photographs revealed an increase in shrub cover in the last half-century. The changes were observed over a 220,000 km^2 tract of arctic tundra, and it is likely that they are more widespread. A quantitative method for comparing the photographs yielded an increase in alder shrub cover from 14 to 20%, with similar increases observed for willow and birch shrubs. This shrub expansion was observed in many landscape positions, including hill slopes, river terraces, and also river floodplains, where the increase in shrub vegetation has resulted in the narrowing and stabilization of floodplains. The regional expansion of shrubs documented in the photographs can only be explained by a perturbation operating on a similarly large scale. In the absence of large-scale disturbances like fire, the increase in shrubs documented here is most likely to be a product of elevated temperatures and other changes in climate favorable to shrub growth.

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ACKNOWLEDGEMENTS

This work could not have been possible without the valuable direction and insightful contributions from Dr. Matthew Sturm, Dr. Charles Racine, Dr. Shusun Li, Dr. F. S. Chapin III, and Dr. Vladimir Romanovsky. This work was supported by the National Science Foundation OPP Award 0119374.

INTRODUCTION

The Earth has been warming in recent decades, and this warming has been most pronounced at high latitudes (ACIA, 2004)(Serreze et al., 2000)(Figure 1). Evidence suggests that the terrestrial Arctic is changing in response to this warming. Permafrost, glaciers, and Eurasian river discharge are several components of the Earth system showing changes consistent with a warming climate. Warmer temperature profiles from boreholes in frozen ground show that permafrost is warming (Lachenbruch and Marshall, 1986; Lachenbruch et al., 1982; Serreze et al., 2000), arctic Alaskan glaciers have retreated in recent decades (Arendt et al., 2002), and Eurasian rivers have increased their discharge over the last century (Peterson et al., 2002).

Widespread changes in vegetation have been more difficult to detect, because (1) the record from test plots extends only 25 years into the past, and (2) these plots are limited to few sites. The plots do show, however, that over the last two decades, arctic shrubs have thrived under experimentally elevated temperatures, and that there have been subtle shifts in species composition in unmanipulated plots consistent with increasing shrubs (Chapin et al., 1995). Over a similar time period, satellite images show a "greening" Arctic (Jia et al., 2003; Myneni et al., 1998), but the images are difficult to interpret (Fung, 1997).

Using aerial photographs, it has been possible to extend our assessment of vegetation change to a much larger area than the plot studies, and over a longer time period than both the plot studies and the satellite vegetation monitoring. Sturm et al. (2001) offered a glimpse of the changes taking place in northern Alaska. The work here

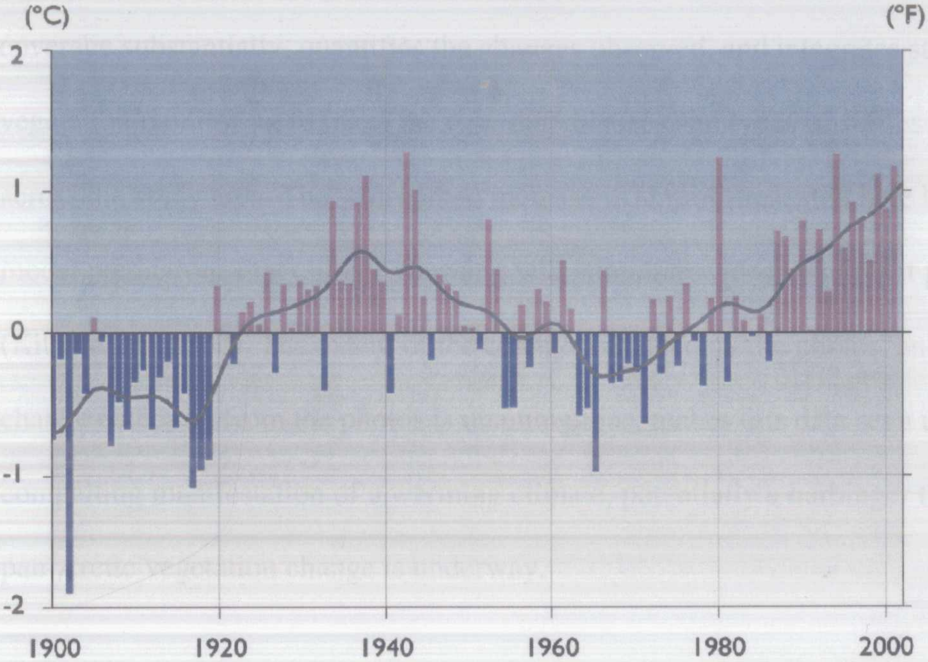

Figure 1. Annual temperature anomalies (bars) and running average (smooth line) from terrestrial stations (60-90°N) relative to the 1961-1990 average (ACIA, 2004).

more than triples the number of repeated old photographs (202), broadens the spatial coverage substantially, quantifies the changes observed, and integrates satellite vegetation monitoring to make the case that all sizes and types of shrubs are increasing across the study area. The widespread increase in shrubs presented here is consistent with model predictions that climate warming will stimulate widespread plant production (Kittel et al., 2000). The extent of the change indicated by the photos, and the fact that change detection from the photos is unambiguous, makes this data set a unique and compelling manifestation of a warming climate, potentially a harbinger that an extensive pan-Arctic vegetation change is underway.

STUDY AREA: NORTHERN ALASKA

The region covered by the original and repeat photographs stretches from the southern extent of the Brooks Range in the south to the Colville River in the north, and from the Chukchi Sea in the west to the Canning River in the east (Figure 2). The area of this region is roughly 220,000 km^2 – about the size of Kansas. It consists of two distinct physiographic provinces (Reed, 1958). The northern province, the Arctic Foothills, is a vast, rolling treeless tundra ecosystem cut by north-flowing rivers. The southern province, the Brooks Range, is an east-west trending mountain range 700 km long and 130 km wide. Rivers flow northward from their headwaters in the Brooks Range, across the gently undulating Arctic Foothills, to their eventual confluence with the east-flowing Colville River or the Arctic Ocean. The river valleys of the Foothills are typically broad and incised between 20 and 200 meters, leaving much of the region covered by relatively flat topography between river valleys, herein referred to as interfluvial benchlands.

The climate of the study area is dominated by long, cold winters and short, cool summers. Annual precipitation is low, but the prevalence of continuous permafrost prevents infiltration and results in soils that remain saturated throughout the summer. The soil-climate system can be characterized as a seemingly paradoxical "arid wetland," with its low precipitation but waterlogged soils. Typical soils in the study area are composed of 5-30 cm thick peat layers overlying silt-rich horizons, which extend down to perenially frozen ground at 30-80 cm (Bockheim et al., 1998).

The region is blanketed by tundra and shrub tundra, specifically (1) nontussock- and tussock-sedge, dwarf-shrub, moss tundra, (2) erect dwarf- and low-shrub tundra, and

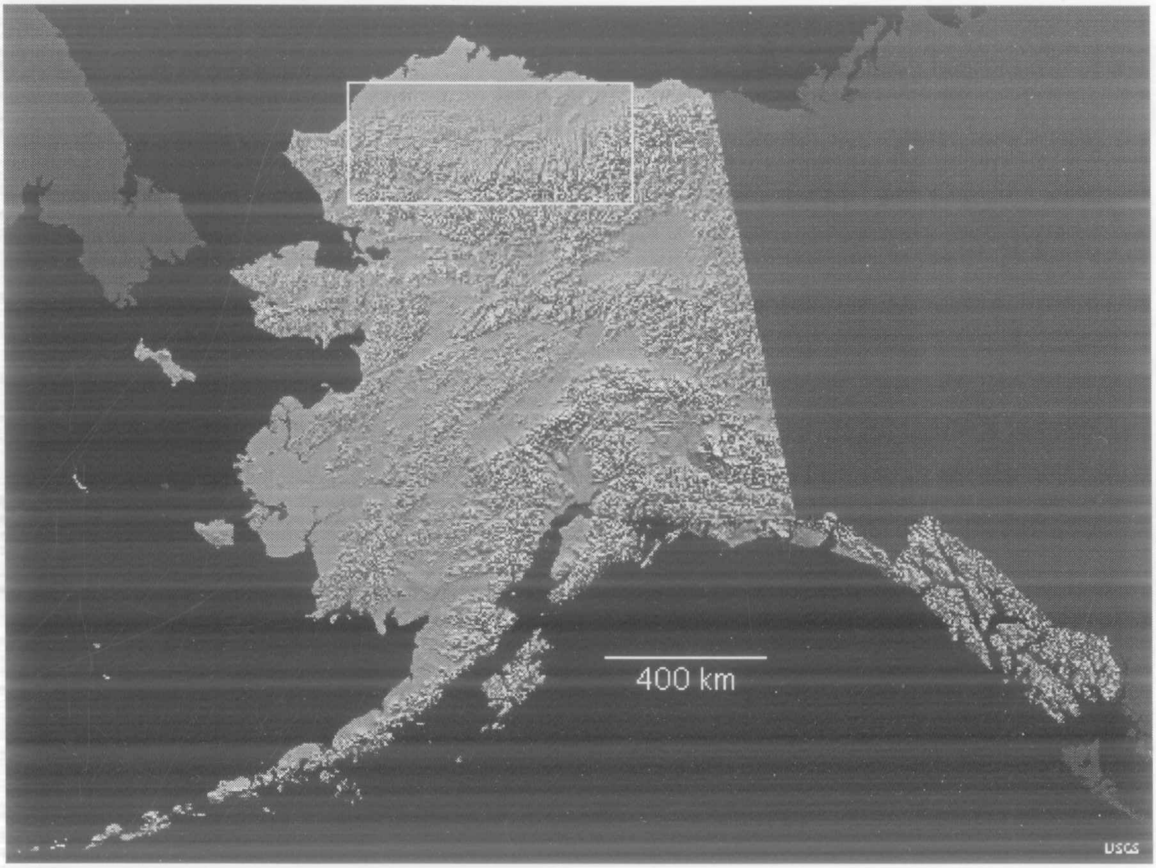

Figure 2. The study area, containing the Brooks Range in the southern section and the Arctic Slope in the northern section.

(3) mountain vegetation growing on non-carbonate and carbonate bedrock (CAVM Team 2003). Shrubs include birch (*Betula nana, Betula glandulosa*), willow (*Salix alexsensi, Salix pulchra, Salix glauca*), and alder (*Alnus crispa*), and the pollen record suggests that the relative percentage of these shrubs has varied little since the transition from dry to mesic tundra in the early to middle Holocene (Oswald et al., 1999). Birch, typically 20-50 cm tall, is very common in the study area, growing between tussocks on open tundra, as well as in protected drainages and floodplains. Willow shrubs of similar height can also be found in inter-tussock spaces, while willow shrubs 2-5 m tall thrive in braided floodplains, water tracks, and protected areas. Alder shrubs of similar height – considered an indicator species for broader vegetation shifts within the study area (Oswald et al., 1999) – are less common. They are found on valley slopes, protected areas, and river terraces within certain regions (Figure 3). These alder also fix nitrogen in what is generally considered a nitrogen-limited ecosystem (Chapin et al., 1995).

Three distinct types of alder are found in the region: "Slope alder" are typically 1.5-4 meters tall and have a bulbous form with prostrate stems, while "crewcut alder" are typically less than 1.5 meters tall and have a skeletal form with erect stems. They derive their name from the crewcut appearance they give to the landscape. "Shock troop" alder share some physical characteristics with the slope and crewcut alder, but distinguish themselves from the others by their landscape position and diffuse, random distribution. The distribution across the river terraces resembles that of troops rapidly spreading out and securing an area.

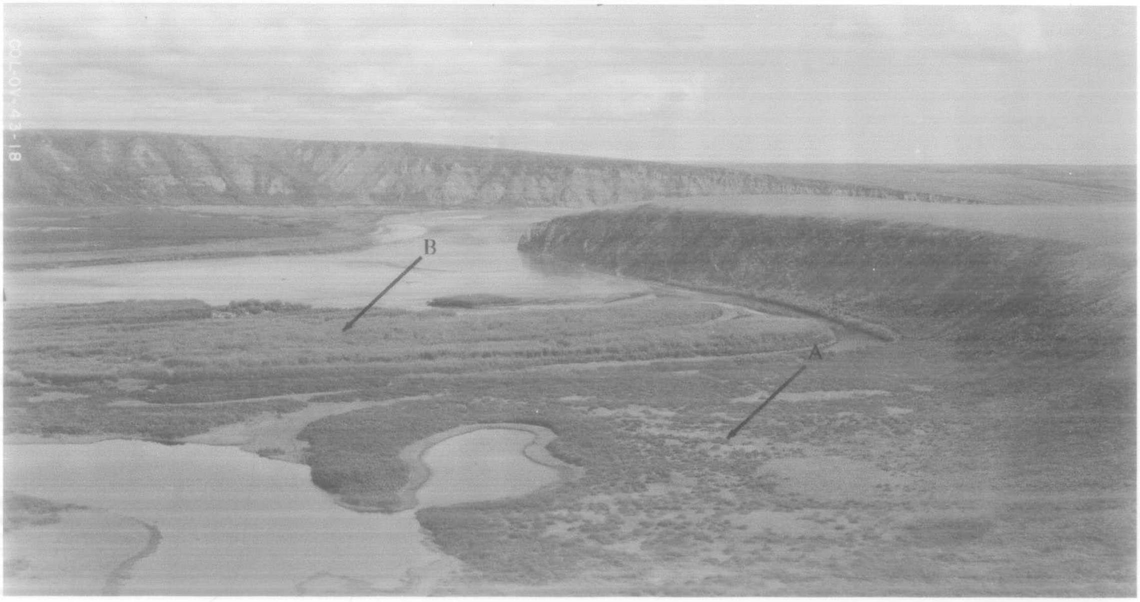

Figure 3. A typical photo from the Col-Photo archive. This photo, COL-OV 43-18, is of the Colville River, near the confluence of the Colville and Oolamnagavik Rivers (N68° 56.80', W154° 02.50'). (A) 2-3 m alder shrubs. (B) 2-4 m floodplain willow shrubs. Present on the benchlands are <1 m birch shrubs, but they are hard to detect in the photo.

The lower part of Figure 4 is an idealized cross-section of a river valley, showing the landscape positions where willow, birch, and the different types of alder are found. Slope alder grow on steeper valley slopes and are particularly abundant where geologic strata intersect the surface and create a break in slope. Crewcut alder grow on gentler valley slopes, oftentimes connecting the broad interfluvial benches to the steeper valley sides. Slope alder individuals are usually distributed randomly, while crewcut alder individuals are distributed evenly across the landscape (Chapin et al., 1989). Slope alders are ubiquitous throughout alder's range, while crewcut alders are limited to shallow upland slopes in areas where slope alders are also thriving. Shock troop alders occupy a unique niche: They are found on stabilized river terraces.

The study area has had no large-scale ecological or human disturbance, other than that attributable to riverine erosion along floodplains. It is unlikely that any pervasive, rapid shifts in vegetation have been caused by conventional disturbance. Due to the presence of standing water, saturated soils, short summers, or lack of lightning, fire is uncommon, particularly north of the Brooks Range (Gabriel and Tande, 1983). In the 100+ hours spent flying and photographing the study area, a small fire scar was seen in only one location.

The study area represents roughly 5% of the vegetated Arctic and includes a large fraction of several of the major tundra ecosystems (CAVM Team, 2003). Changes similar to those documented herein could be occurring throughout the pan-Arctic.

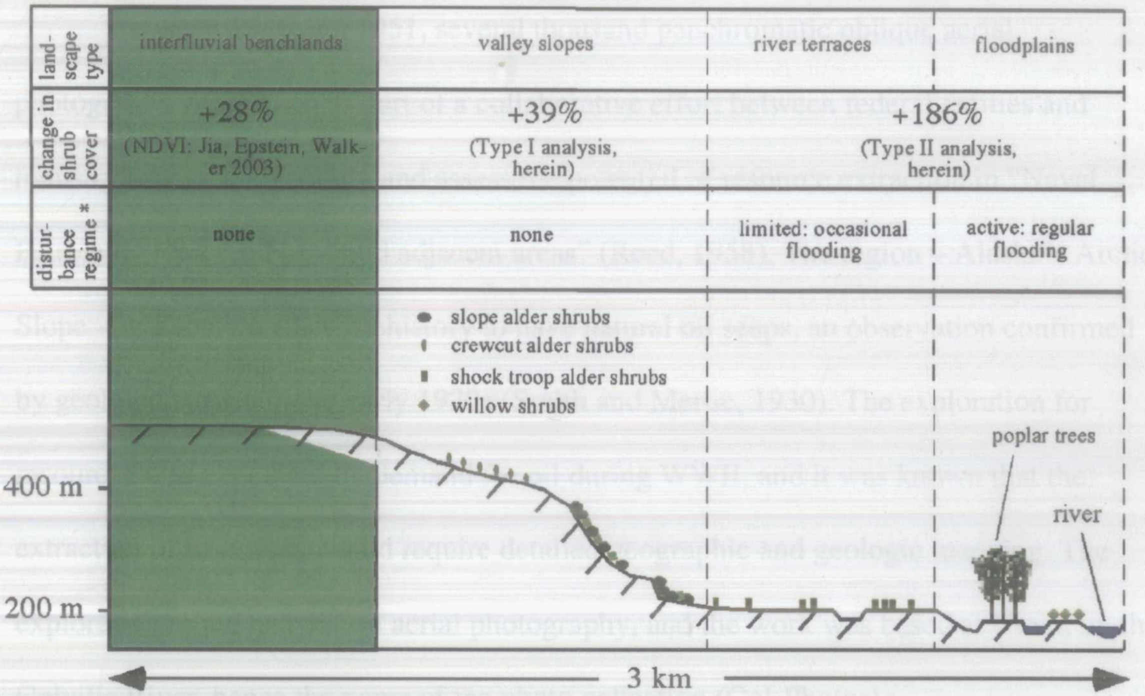

Figure 4. An idealized cross-section of a typical river valley was compiled from 23 river valley cross-sections. It shows landscape positions occupied by different types of large shrubs, and is typical of the valleys of the central Arctic Slope. Not depicted here are 0.5-1 m birch shrubs, co-occurring with alder and willow throughout this figure.

* Refers to disturbance regime on larger scale.

THE COL-PHOTOS

Between 1946 and 1951, several thousand panchromatic oblique aerial photographs were taken as part of a collaborative effort between federal entities and industry to map the geology and assess the potential of resource extraction in "Naval Petroleum Reserve No. 4 and adjacent areas" (Reed, 1958). The region – Alaska's Arctic Slope – was known since prehistory to have natural oil seeps, an observation confirmed by geologic parties in the early 1920s (Smith and Mertie, 1930). The exploration for resources was expedited by demand for oil during WWII, and it was known that the extraction of resources would require detailed geographic and geologic mapping. The exploration relied heavily on aerial photography, and the work was based at Umiat on the Colville River, hence the name of the photo collection (Col-Photos).

Multiple military photo squadrons were responsible for the trimetrogon, vertical, and oblique aerial photography. The oblique photography used in this study was taken by Air Force Photographic Squadron 1, based out of Big Delta, located 60 miles southeast of Fairbanks. The squadron, consisting of 4 Liberators and 2 Beechcraft airplanes, focused their efforts on areas where rocks were exposed, primarily the river valleys of the Arctic Slope and Brooks Range (Reed, 1958). The photos were used to interpret the structural geology of the region and to locate oil-bearing rocks.

The camera used to take the original photographs was the K-18 24-inch Fairchild camera that produced 18×9 inch negatives. A partial set comprising several thousand 18×9 inch black and white contact prints from the old negatives was used for this study. Because the negative size was so large, the resolution of the contact prints is very high, making them ideal for comparing to modern photos for landscape and vegetation changes.

The original photos were taken out the side door of small twin-engine Beechcraft and Liberator airplanes. The method used to acquire the original photographs was to fly up and down a river valley while photographing the river and facing valley slopes. Some flight-lines also include landscapes of open tundra. The photographs, taken during summer months of 1945-53, were acquired with such rapidity and regular frequency that the terrain coverage along most river valleys is continuous. Primitive USGS (United States Geological Survey) 1:250,000 scale maps were used to record the roll number and location of the photography flight lines, and although some inaccuracies exist, the maps are helpful in locating and repeating the old photographs. Details regarding film exposure, processing, aircraft, and crew are described in the original protocol for aerial photography, included here as Appendix A.

METHODS

Of the several thousand Col-Photos available, we were able to repeat 202 between 1999 and 2002 for the purposes of assessing vegetation change. These were selected to produce a wide geographic coverage and the greatest likelihood of detecting change. Many of the Col-Photos do not show any visible shrub forms, either because there were no shrubs, or because the shrubs in the area were small and blended in with other tundra vegetation. About 20% of the photos contain dark and distinct shrub forms, typically large alder, surrounded by large willow and birch. Each year of the project, the entire Col-Photo contact print collection was perused for photographs from parts of the study area not yet re-photographed, yet containing visible shrubs, and these photos were chosen for re-photography. Some regions of the study area contained few distinct shrub forms; a few photos from these regions were repeated to achieve widespread geographic coverage.

Using the index maps to determine the general location of an original photograph, a resection technique was applied to determine the exact location from which the original photograph was taken (Moffitt, 1959). This technique involves determining the angles separating known geographic features identified in the old photos and then using a 3-arm protractor to infer the position on a USGS map. After two summers' training, we found we could determine camera locations by inspection with the same accuracy as the resection technique, so we switched to this faster method. The altitude of the aircraft was estimated using the position of landscape features relative to the horizon. The old camera locations were entered into the helicopter GPS (Global Positioning System), the positions were reoccupied, and the landscapes were re-photographed from about the same perspective as they were a half-century earlier. It was necessary to have an unobstructed view of the landscape to avoid reflection and yellow-tinting from the aircraft windows, so the doors of the helicopter were removed.

In order to make the comparison of old and new photographs easier, it was important to produce a repeat photo that nearly matched the perspective of the old photo. As the helicopter approached an old photo location, multiple photos were taken of the landscape, and later the best match was selected for change detection. The old photos were carried in the helicopter, and landscapes viewed through the camera lens were compared with these old photos to fine-tune the helicopter's position. It was sometimes necessary to circle back and re-do the photographs from a slightly different location. None of the repeated photographs ever matched perfectly with the old photographs, but most repeated photos had a perspective that was close enough to that of the old photograph to allow analysis.

The high resolution of the old photographs demanded repeat photographs of comparable resolution. Unfortunately, the camera used for the original photographs was too cumbersome and expensive to operate. Instead, a medium format Mamiya RZ67 Pro II camera with Kodak Portra 400 ASA color film was used. The medium format camera, with its 6 X 7 cm landscape negative, allowed for high resolution color photography. F-stops varied to maintain shutter speeds of 1/250 and 1/400 seconds.

Some consideration was given to using black and white film for the repeat photography, but in the end we chose to use color film because (1) color images can be converted to greyscale, and (2) people seeking to repeat the photographs in the future will probably prefer the additional information contained in color film. Film was chosen over a digital format because of its higher resolution and permanence as a method for storing data. Film from all old and new photography was scanned using the Nikon Super Coolscan 8000 (4000 dots-per-inch resolution), and pairs of photos were cropped to provide best possible matches.

The 202 old photographs repeated covered segments of 19 rivers and 5 open tundra benches, for a total of 24 “photo-lines” (Figure 5). Each photo-line includes from 2 to 18 paired old and new photographs and ranges from 3 to 40 km long. The 24 photo-lines are scattered throughout the Brooks Range and Arctic Foothills.

To improve and test our interpretation of the photographs, we identified and mapped the vegetation that appears in 9 photos by going to those locations in the field. These were located on the Ayiyak, Chandler, Sagavanirktok, and Kugururok Rivers. Using spotting scopes and two-way radios, one or two people would traverse the area shown in the photograph, communicating the vegetation size and assemblages to the person behind the spotting scope. The person behind the scope would associate that information with a point placed on both the old and new photographs (Figure 6). This process (1) allowed for accurate, calibrated photo-interpretation, (2) made us aware of how large the shrubs were (larger than expected from the photographs), and (3) made us aware of the prevalence of willow and birch, which are difficult to see in the photos, in close association with alder.

Shrubs were sampled to determine the age structure of shrub patches and the age structure of individual clumps of stems. Discs were cut from every stem in a clump, and

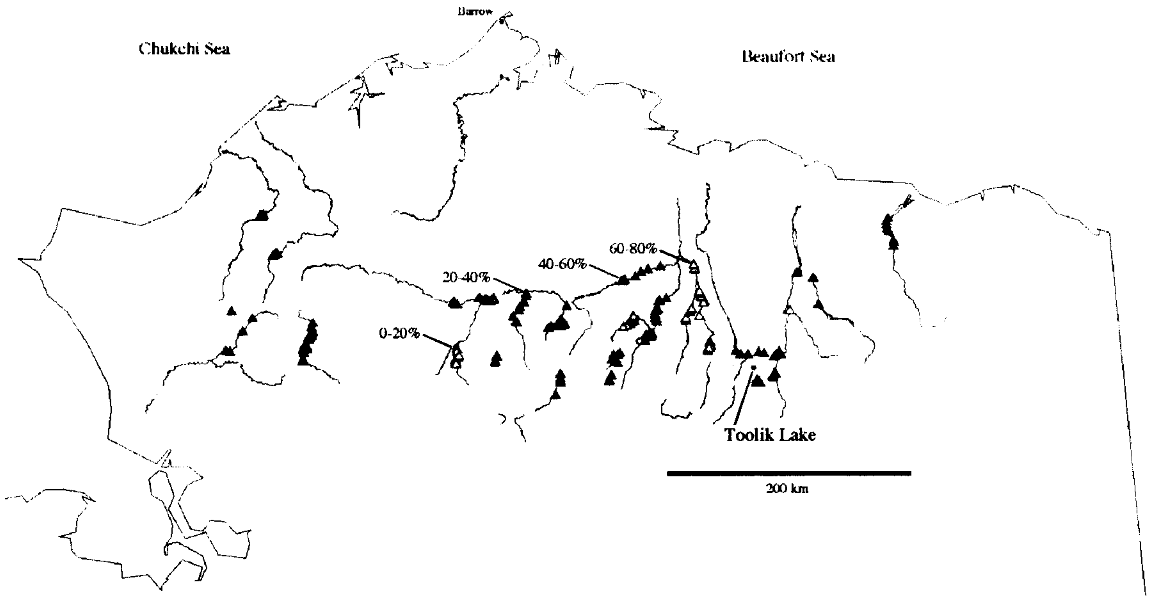

Figure 5. The triangles on the map denote the locations of all 202 repeated photographs used in this study. The color of the triangle denotes the average percent increase in shrub cover for the entire photo-line (yellow = 0-20%, yellow/orange = 20-40%, orange = 40-60%, red = 60-80%). Black triangles denote photographs that had few or no visible shrubs.

42-17 subset

Figure 6. A photograph of the Chandler River valley (top) taken in 2001 (N68° 49.39', W152° 0.52'), one of the locations where field mapping was conducted. The numbers and letters on the inset (bottom) correspond to descriptions and close-up photographs of the vegetation (see Appendix B for vegetation assemblages).

growth rings were counted so that the age of the oldest live stem in an individual shrub could be determined.

Recent research has documented increases in the satellite vegetation index NDVI (Normalized Difference Vegetation Index) in the study area (Jia et al., 2003). Satellite imagery was used in this study to determine the contribution large alder and willow shrubs make to the NDVI signal. A Landsat ETM+ image from the central Arctic Slope and Brooks Range was chosen. The NDVI algorithm, (near IR + red) / (near IR – red), was applied to the image using ENVI (Environment for Visualizing Images) software. The NDVI image was then compared with Col-Photos and modern photos containing large alder and willow shrubs. By examining NDVI values in the image and noting where large shrubs were present on the landscape, we determined that large shrubs were nearly or completely saturating the NDVI signal (Figure 7).

Photo Assessment

Most photos in this study cover about 11 km^2 of terrain, including the foreground (1 km^2), middleground (2 km^2), and background (8 km^2). The foreground usually includes the floodplain and old river terraces, the middleground usually includes the facing valley slope, and the farground, when present, stretches obliquely to the horizon. In each photo, we were able to reliably assess about 2.5 km^2 of the foreground and middleground for changes in vegetation. A conservative estimate of the actual area assessed for the study is 500 km^2.

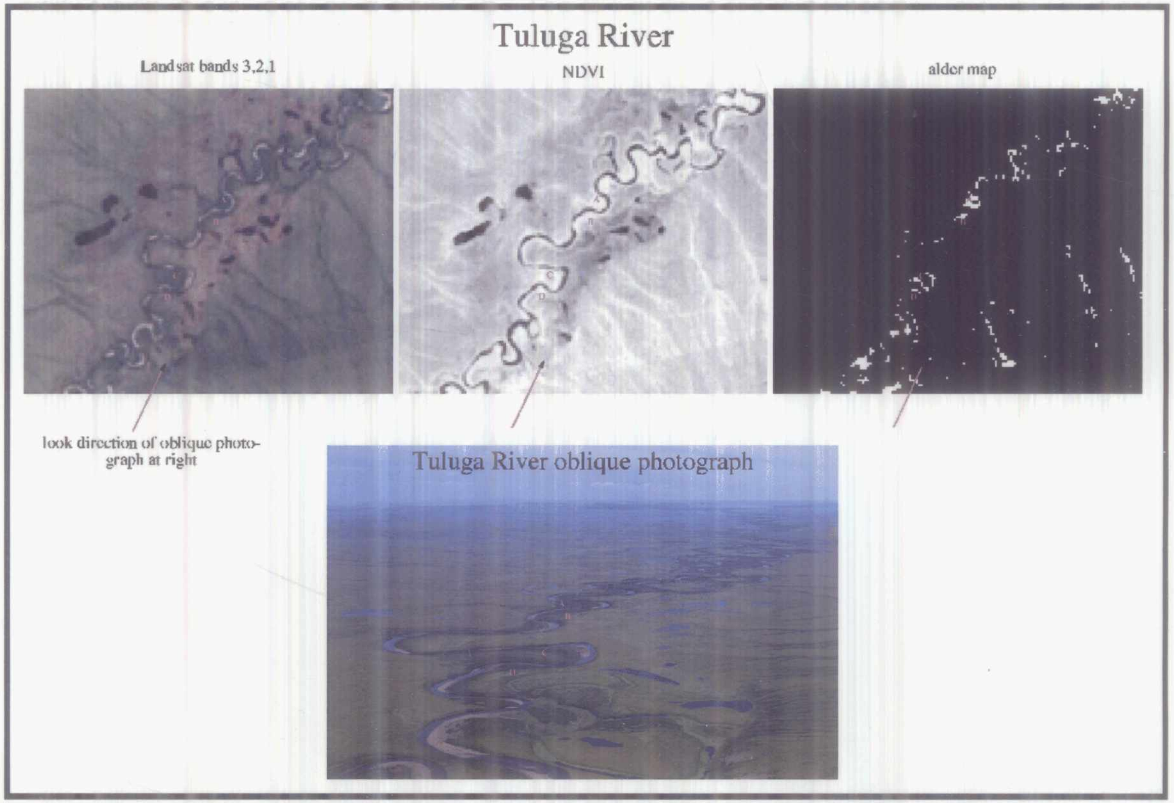

Figure 7. Tuluga River (N68° 57.50’, W151°30.00’). Oblique photography was used to empirically determine alder’s contribution to the NDVI signal. Note that the saturated white pixels in the alder map match the dark alder shrubs in the oblique photograph, demonstrating that NDVI cannot assess change for larger shrubs.

Inter-tussock birch and willow shrubs were often the same color as the background tussock tundra, so change detection for these shrubs was possible only when they were part of the foreground, or when they were adjacent to rocks and dark shrubs, against which their growth could be gauged. Larger shrubs, particularly alder shrubs, have a distinctive dark shade and bulbous form, making it possible to tell if they have changed in size or number from the old to new photographs.

Most of the photo-pairs were not exact matches, but we developed a method to quantify the change from old to new. Initially, we attempted to use photogrammetric software to shift the perspective of the new photo so that it would exactly match the perspective of the old photo, but the low obliquity of the photos, plus the close proximity of topography, led to little improvement in the resulting "corrected perspective" image. Instead, two types of analysis were devised to break the landscape down into smaller sections from which comparisons of old and new could be made.

In Type I analysis, a gridding system was applied to dissect the photos into smaller sections. A grid that divided the old photo into sections was drawn on acetate and overlain upon the photo (Figure 8, top). The grid was then transferred line by line using identifiable tie points to a piece of acetate overlaying the new photo (Figure 8, bottom). If both photos had been taken from the exact same location and both lenses were identical, then the grid covering the old photograph could be overlain on the new photograph exactly, without distortion, and each grid cell in the old photograph would cover the exact same section of terrain in the new photograph. Because the perspective of the repeat photograph was never a perfect match, the grid manually drawn on acetate overlying the

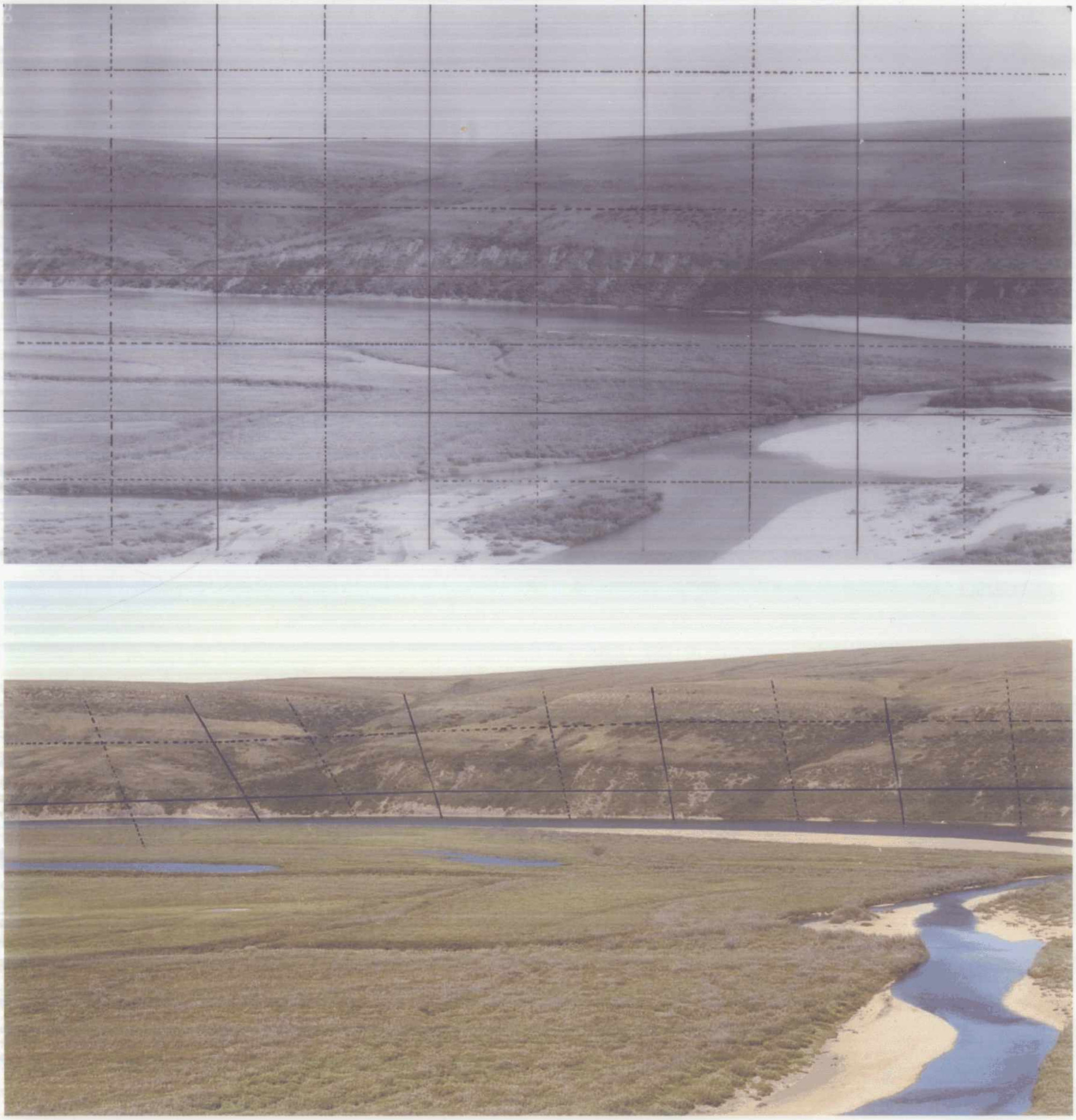

Figure 8. A photo-pair from the Colville River (N68° 56.77', W155° 57.58'), showing the rectangular grid overlying the old photo (top), and the warped grid overlying the new photo (bottom). The foreground in the new photograph is not gridded because the distortion in the new grid becomes exaggerated nearer to the camera lens.

new photograph was always distorted to varying degrees. Furthermore, distortion in the new grid became exaggerated in the foreground (nearer to the camera lens). Thus the Type I analysis was confined to the stable valley slopes in the middleground of the photographs. All photograph-pairs (86) that showed a limited amount of distortion in the new grid were quantitatively analyzed cell by cell for percent shrub cover.

One of the key change metrics we report here is percent change in shrub cover. In this study, the percent shrub cover refers to the percent of large (> 0.5 m tall) dark, identifiable shrubs on an otherwise fine-textured background (Figure 9, middle). Grid cells with no visible shrubs in the old and new photographs were not assessed. Percent cover for a given photo-line was determined by summing the area covered by dark shrubs in the gridded photographs of each region and dividing by the total gridded area containing shrubs for each region.

The technique used to estimate percent cover within a grid cell involved three types of comparator cards. One type of card had shrub-sized circles of various densities spread evenly over grid cells. The second type of comparator card had a combination of clumped and scattered shrub-sized circles, again of various densities. The third type of card had all of the dark material concentrated in a corner, in various sizes. Using these three comparator cards in parallel, estimates of percent cover were made.

A subset of the manual gridded percent cover estimates were tested against computer-derived percent cover estimates to test the accuracy of the manual estimates. Although the difference in perspective between old and new photos prevented digital comparisons of old and new landscapes, the difference in perspective could be reduced

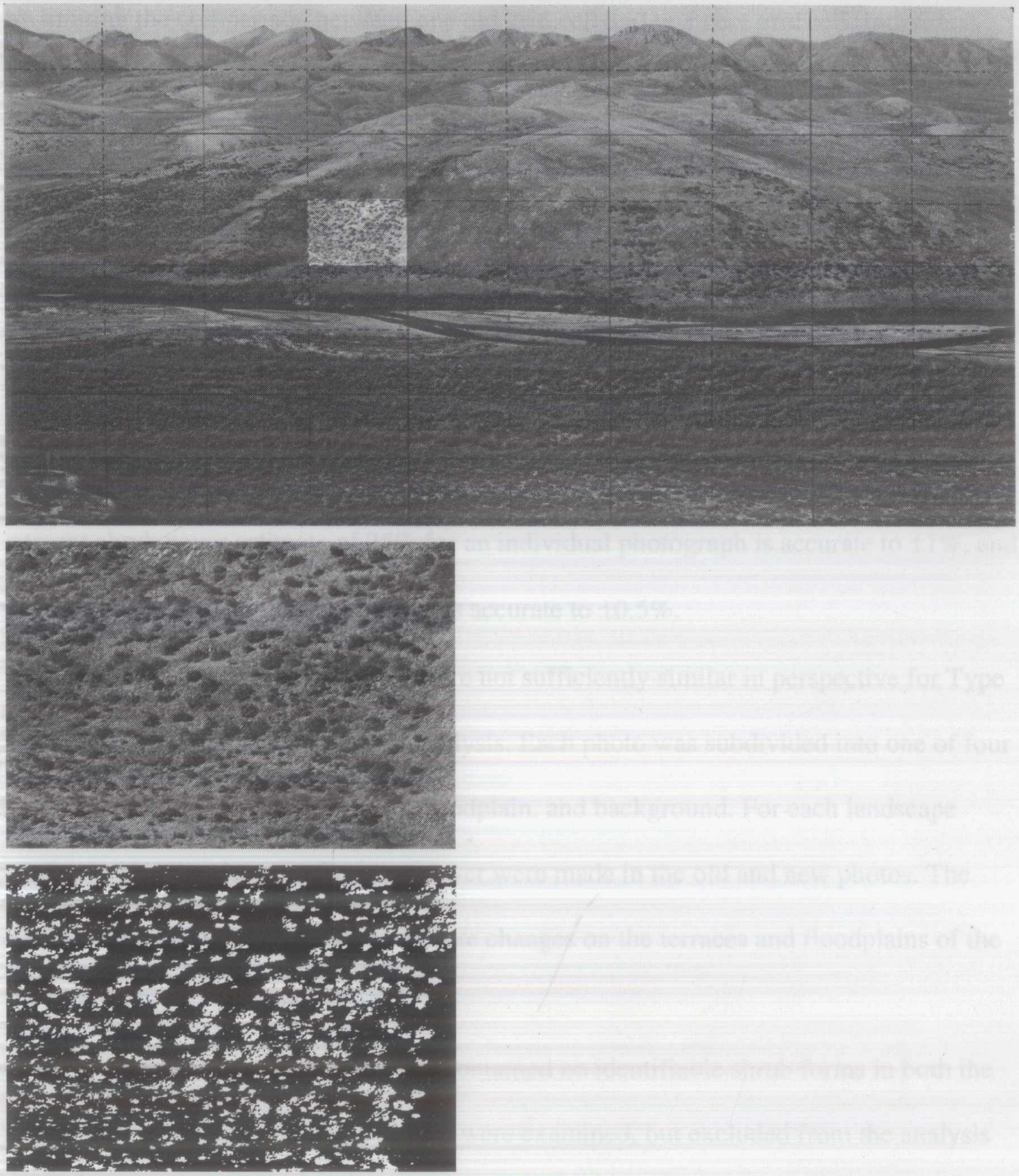

Figure 9. A 1949 photo of the Nimiuktuk River (N68° 23.08', W159° 50.57'). An individual grid cell (middle), subset from an old photo (top), was converted to a binary image (bottom, shrubs are white) for the purpose of estimating percent shrub cover. The manual estimate of cover for this grid cell was 17%, and the computer-derived estimate of was 21%.

by limiting the comparison between one old grid cell and one new grid cell. Individual grid cells were selected from different photographs and subset from the image. The resulting subset grid cell was then converted to a black and white image, in which alder was white and tundra was black (Figure 9, bottom). Percent cover was then determined by calculating the mean of the binary 2-dimensional array that represented the grid cell. Comparing the electronic estimates of percent cover to the visual estimates revealed a difference of 4% over 20 grid cells composing a typical photograph. In this case, 4% error represents 4% of the actual percent shrub cover estimate. Therefore, an overall percent shrub cover estimate of 25% for an individual photograph is accurate to ±1%, and a percent shrub cover estimate of 12% is accurate to ±0.5%.

Sixty-eight photographs that were not sufficiently similar in perspective for Type I analysis were subjected to Type II analysis. Each photo was subdivided into one of four landscape categories: slope, terrace, floodplain, and background. For each landscape category, visual estimates of percent cover were made in the old and new photos. The Type II analysis was also used to evaluate changes on the terraces and floodplains of the 86 photos in the Type I analysis.

The remaining 48 photographs contained no identifiable shrub forms in both the old and new photographs. These photos were examined, but excluded from the analysis because the metric for change that we used – shrub cover – had no meaning. In the end, 154 photo-pairs underwent Type I (86 photo-pairs) or Type II (68 photo-pairs) analysis, and 48 photo-pairs containing no distinct shrub forms were excluded from formal analysis.

RESULTS

In the last half-century, shrubs increased in abundance in river valleys throughout the study area. Shrub patches showed patterns of increase that can be classified as (1) boundary expansion, (2) patch infilling, and (3) individual growth. These three types of change typically occurred together. Figure 10 is a photo-pair showing the three types of change: The edges of shrub patches have expanded several meters, there are new shrubs growing within the bounds of the old patches, and many of the individual shrubs present in the old photos are noticeably larger today.

Geographic Patterns of Shrub Increase

The changes reported in Table 1 are for the 86 photograph-pairs subject to the Type I analysis, so they are representative of stable valley slopes. The change in shrub cover ranges from a low value of +3% increase (6.7 in old photos to 6.9% in new photos) on the Lupine River to a high value of +71% increase (8 to 13%) on the Oolamnagavik River. Eighty of the 86 photo-pairs registered an increase in percent shrub cover, while the remaining 6 photo-pairs registered no change. No photo-pairs registered a decrease in shrub cover. The shrub cover over the entire ensemble of 86 photos went from 14 to 20% over the last half-century, representing an increase of 39% in large shrub abundance.

This increase can be computed another way. The 86 photos submitted to the Type I analysis contained a total of 1209 grid cells with identifiable shrubs, each cell covering an area roughly 160 X 160 m. Of the 1209 grid cells, 812 registered an increase in shrubs, 384 registered no change, and 13 registered a decrease in shrubs. This means that 67% of

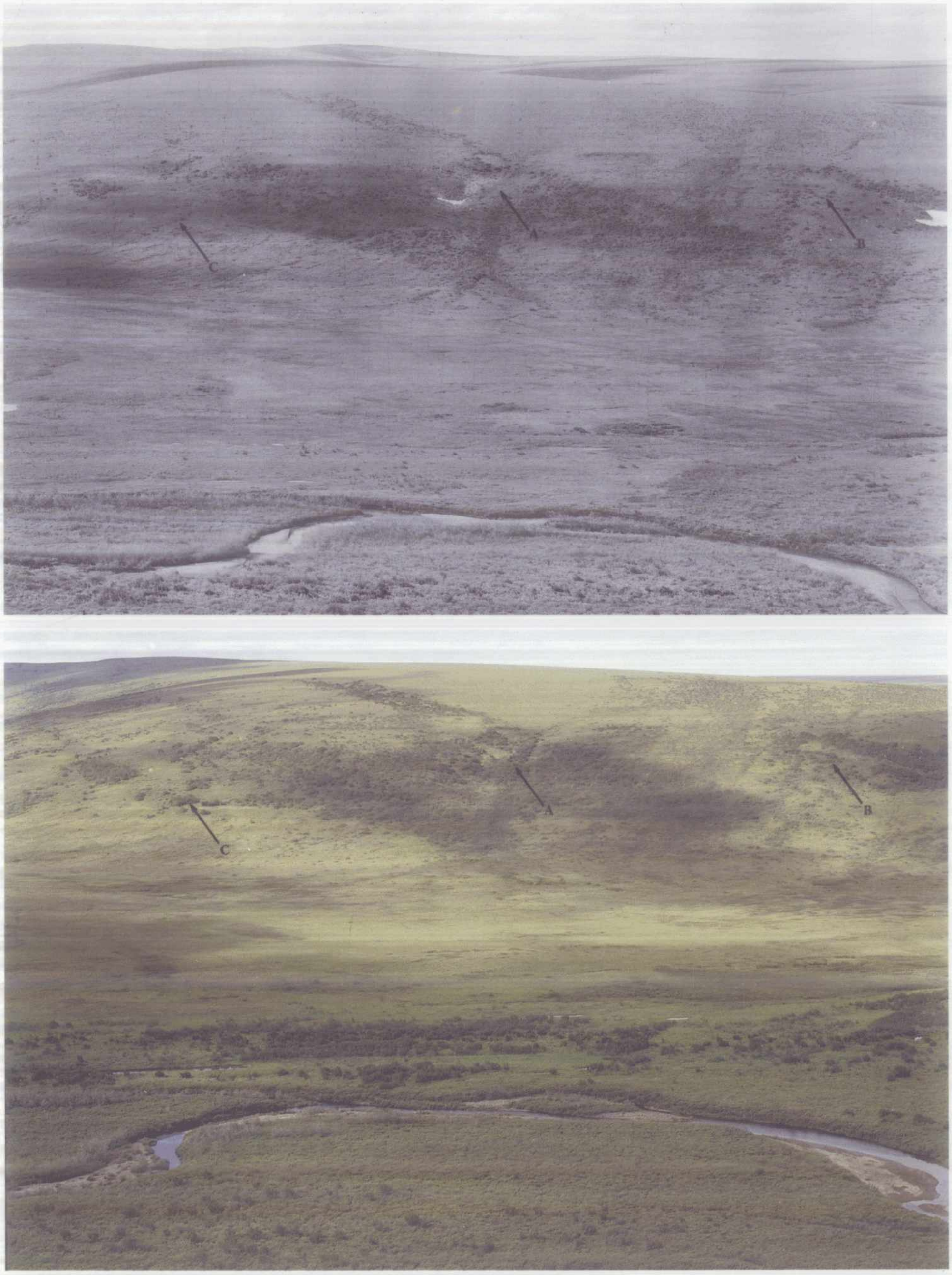

Figure 10. The Oolamnagavik River (N68° 52.00', W154° 8.36'), in 1949 and 2002. The photo illustrates the three types of shrub increase: (a) The edges of shrub patches have expanded 1-10 m, (b) there are new shrubs growing within the bounds of the patches, and (c) many of the individual shrubs present in the old photos are larger today.

Table 1. Results from the Type I analysis for 86 of the 202 photo-pairs.

Photo-line	Number of photos	% dark shrub cover, 1947-1951	% dark shrub cover, 1999-2003	% change in dark shrub cover	stdev, % change, per photo
Anaktuvuk R. (S)	2	13	16	20	29
Anaktuvuk R.(N)	4	14	17	22	19
Ayiyak R.	2	7	8	23	81
Chandler R.	12	28	37	35	36
Colville R. (W)	6	5	8	67	42
Colville R.	9	17	23	36	30
Colville R. (E)	4	21	28	37	11
Kurupa R.	7	9	14	55	25
Lupine R.	2	6.7	6.9	3	3
Nanushuk R. (S)	4	18	21	17	7
Nanushuk R. (N)	4	16	20	20	14
Nigu R.	3	8	10	16	15
Nimiuktuk R.	14	12	16	38	55
Oolamnagavik R.	10	8	13	71	47
Sagavanirktok R.	3	8	13	61	10
N. Alaska	**86**	**14**	**20**	**39**	**40**

the cells evaluated experienced an increase in shrubs, 32% were unchanged, and 1% experienced a decrease in shrubs.

The increase in shrubs varied in magnitude across northern Alaska, with the greatest increases documented on the central Arctic Slope and Brooks Range photo-lines (Figure 5). These photo-lines are along river valleys at elevations less than 400 m – places where 4-meter alder, 4-meter willow, and 1-meter birch are thriving. River valleys above 400 m – closer to the fringe of alder's range – have seen less increase in shrubs. The river valleys experiencing the most change also tend to be more deeply incised than those experiencing less change.

The Killik River valley is an exception to this pattern because of its unique Quaternary history and unusual surficial deposits. The river valley is filled with lacustrine sediments leftover from the late-glacial period when a 29-mile long proglacial lake filled the valley (Chapman et al., 1964). These lacustrine sediments have since been extensively reworked by aeolian processes into the "miniature desert" found by USGS explorers in 1945 (Chapman et al., 1964). The large increase in shrubs observed in the Killik River valley is most likely a result of its unique ecosystem.

Landscape Patterns of Shrub Increase

The results from the Type I analysis show that large shrubs are increasing on the stable slopes leading down to rivers. The 68 photographs subjected to the Type II analysis confirm this change and also show that shrub cover is increasing on river terraces and floodplains (Table 2). On valley slopes, the Type II analysis showed that

Table 2. Results from the Type II analysis (68 of the 202 photo-pairs)

Photo-line	Number of photos	% shrub cover, slopes 1947-1951	% shrub cover, slopes 1999-2003	% change	% shrub cover, river terraces + floodplains 1947-1951	% shrub cover, river terraces + floodplains 1999-2003	% chan ge
Anaktuvuk R. (S)	2	18	23	28	3	8	167
Anaktuvuk R. (N)	1	35	40	14	3	10	233
Atigun Gorge	1	20	25	25	15	25	67
Ayiyak R.	11	22	38	42	5	9	80
Chandler R.	6	42	60	43	4	10	150
Colville R.	1	15	17	13	3	3	0
Colville R. (E)	3	43	47	9	18	41	128
Itigaknit R.	4	20	21	5	-	-	-
Ivishak R.	3	22	29	32	0	2	high
Killik R.	5	14	27	93	4	13	225
Kokolik R.	2	18	23	28	-	-	-
Kugururok R.	5	19	21	11	1	8	800
Kurupa R.	2	3	6	100	5	9	80
Nanushuk R. (S)	4	19	27	42	3	6	100
Nanushuk R. (N)	4	20	25	25	11	15	36
Nigu R.	7	18	18	0	-	-	
Nimiuktuk R.	5	30	42	40	3	8	167
Oolamnagavik R.	3	25	40	60	3	14	367
N. Alaska	**68**	**22**	**30**	**34**	**5**	**12**	**186**

shrubs increased from 22 to 30%, equivalent to a 33% increase in shrub cover. Based on a two-population analysis of variance (ANOVA), the 33% increase on stable valley slopes is statistically significantly the same ($\alpha = 0.05$) as the 39% increase on stable valley slopes detected using the Type I analysis. The Type II analysis also showed that shrub cover on river terraces and floodplains has increased from 5 to 12%, equivalent to a 186% increase in shrub cover.

The expansion of shrubs across river terraces has been particularly dramatic. While less consistent than the increase on valley slopes, it is more conspicuous. The term "river terrace" is used here to describe stable tundra benches elevated above the river channels. Our field excursions show that, although these terraces may be prone to occasional flooding, the organic layer is undisturbed and spatially continuous, with permafrost often present. Forty-seven of the 72 photo-pairs containing river terraces show expansion of shrubs onto the river terraces, while 25 of 72 photo-pairs show no change and zero show negative change. On river terraces, it is common to see large tracts of shrub-free tundra colonized by large shrubs in the past half-century (Figure 11). This type of increase is concentrated in the more deeply incised valleys.

Thirty-eight of the 49 photo-pairs containing floodplains show that floodplains on the Arctic Slope have more continuous vegetation cover now than 50 years ago, and the rivers seem more channelized now than in the old photos. Eight of 39 photo-pairs show no change in the floodplain vegetation and 3 show negative change. Active floodplains are, by nature, constantly evolving. But superimposed on the typical floodplain evolution over the last half-century is an increase in the amount of vegetated gravel, silt, and

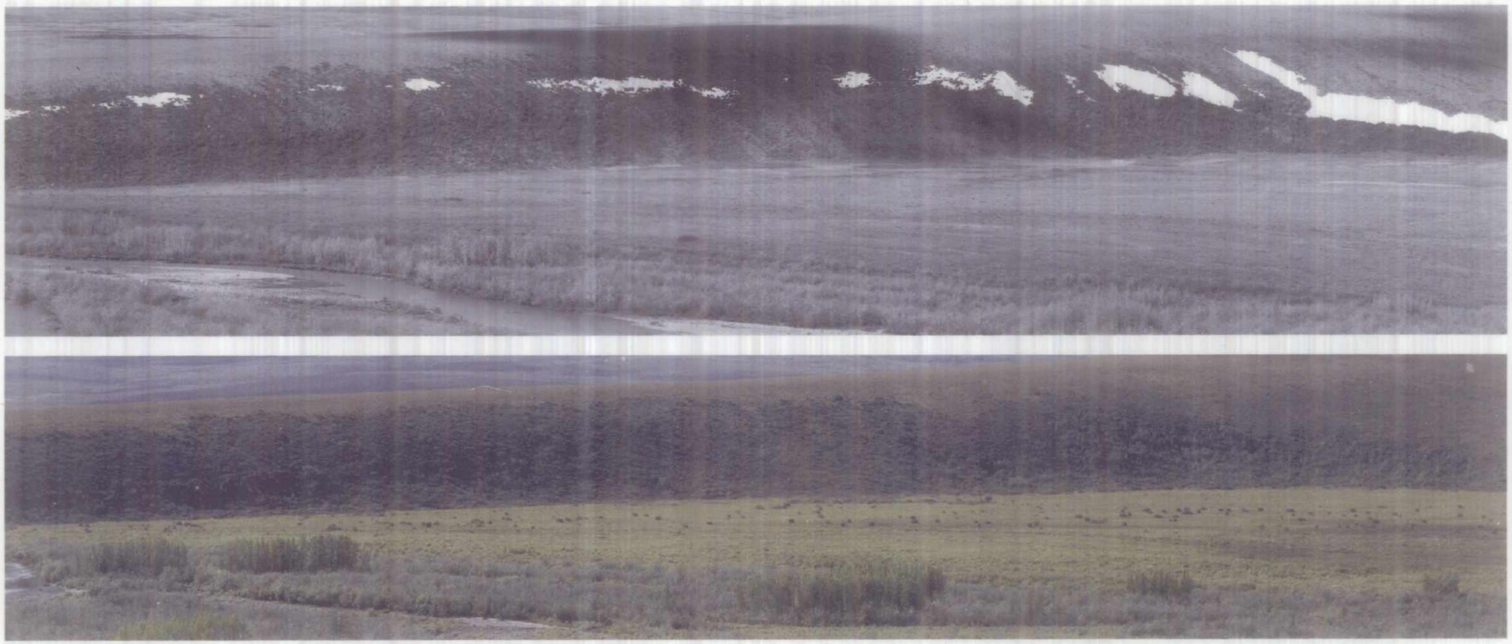

Figure 11. Photographs from the Chandler River (N68° 55.51', W151° 52.45') illustrating the rapid expansion of alder on river terraces.

sandbars covered by vegetation. The bars free of vegetation in the old photos now often host low, non-shrub vegetation in the new photos (Figure 12), and the bars with sparse shrub cover in the old photos now have more shrubs.

The results presented so far apply to landscapes with varying disturbance regimes. Valley slopes contain no large-scale disturbance, river terraces a limited amount, and floodplains contain continual disturbance. As the disturbance probability increases, a greater number of photo-pairs are required to ensure that the changes observed are not merely the result of a disturbance, but the result of a more general trend (Figure 5). The Type I analysis (Table 1) tells a consistent story of shrub increase on undisturbed valley slopes. As we progress away from the Type I analysis, however, the signal of increasing shrubs and vegetation becomes noisier: radical increases and occasional decreases in shrubs and vegetation (oftentimes limited to individual grid cells) are typical. In floodplains, for example, many photo-pairs are necessary to discern the net change in vegetation over the entire study area. It is therefore crucial to realize that (1) figures presented here are merely examples of changes observed in numerous photographs, and that (2) with 202 photographs covering 500 km^2, the consistent patterns revealed are more likely to be general changes than the result of disturbance.

Shrub Species Relationships

During the field mapping, wherever alder was found, large birch and willow were also present. In some cases, the proximity of these different shrub types occurred because they were both exploiting a favorable position in the landscape – a break in slope, for

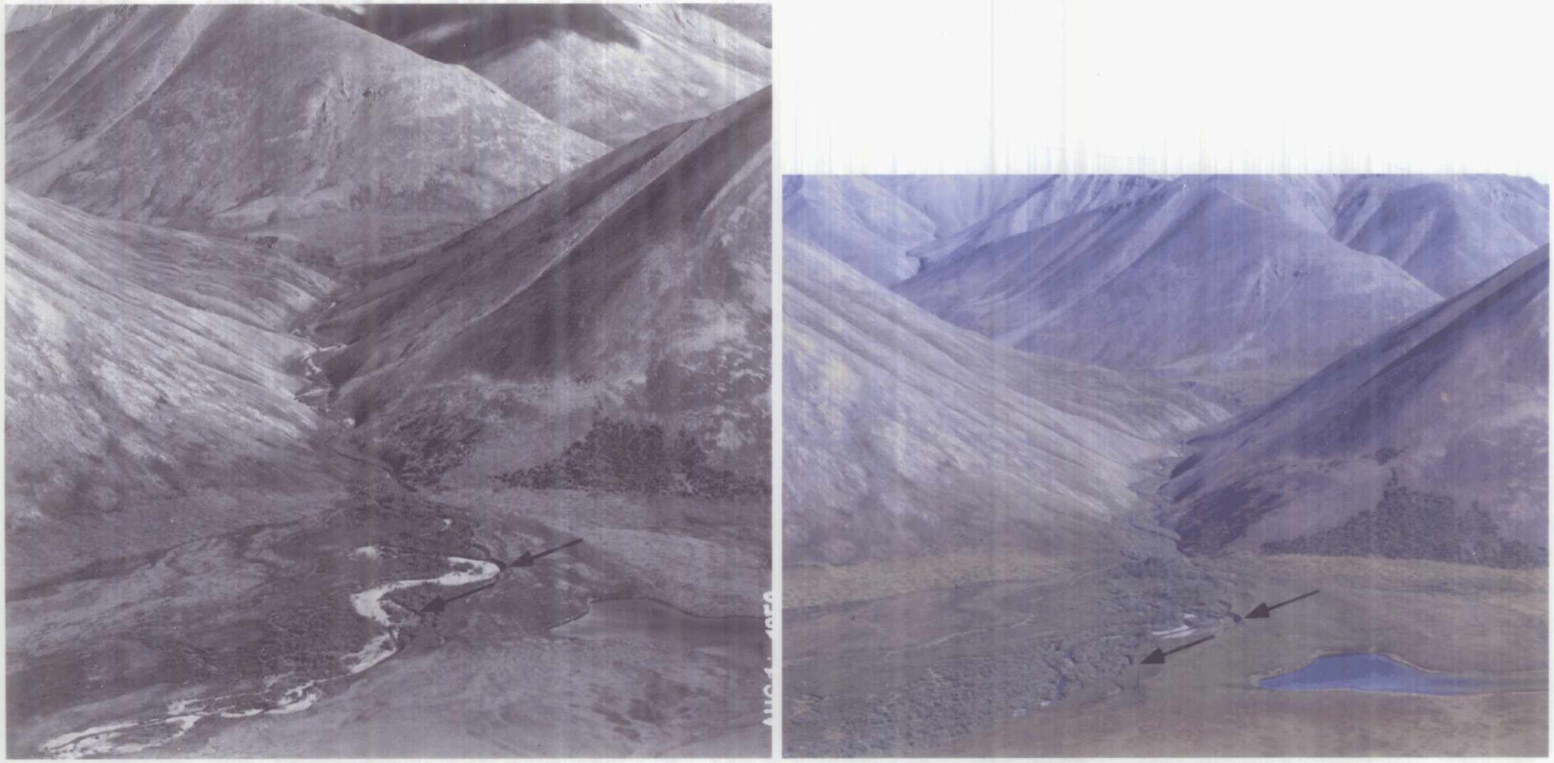

Figure 12. These 1949 and 2000 photos of a tributary of the Kugururok River (N68° 25.14', W161° 15.24') are an example of the increase in floodplain vegetation observed throughout the study area. Notice how much less exposed sandbar is present in the 1999 photograph.

example – not necessarily benefiting from the other's presence. In other cases, 0.5-1.0 m birch and willow shrubs occurred in rings surrounding 1.5-4.0 m alder shrubs, producing striking "shrub halos" (Figure 13). These halos are likely the result of some combination of favorable physical and chemical microhabitats produced by the central, larger shrub. Physically, the large alder shrub acts as a topographic obstacle to the wind, trapping snow, elevating soil temperatures, dropping readily decomposed leaf litter (Shaver et al., 1995), and protecting the immediate area from dessication. Chemically, the alder shrubs also fix nitrogen, providing a key nutrient that promotes growth of the surrounding willow and birch shrubs.

In general it was not possible to assess changes in smaller shrubs like birch and willow, but analysis of a few key photos indicate that there has been a widespread increase in birch and willow, as well as alder, during the past 50 years. In 15 (for willow) and 4 (for birch) pairs of photos, we were able to directly document that these shrub species had increased in size and abundance. In addition, in what appears to be low-shrub or shrubless tundra in the old photographs, a coarser texture indicative of larger birch and willow shrubs is evident in the new photos (Figure 14). Often alder shrubs, which appear as very distinct shrub forms in the old photos, are no longer distinct in the new photos because willow and birch have grown-up around them, forming deep shrub halos. This kind of textural change indicative of willow and birch increase is common (*n*=23) in photographs where the resolution is high enough to make such assessments. To total, the evidence is compelling that not only dark (alder) shrubs have increased in abundance, but also that the increase has been a general one not limited to a single species.

Figure 13. A shrub halo (N69° 01.125', W148° 50.183'). The central area of this photo was the site of a single alder shrub harvested for biomass. The alder was growing in front of the person in the photo, similar in size and adjacent to the one growing behind the person. The halo consists of 0.2 to 0.8 m willow and birch and is outlined in black. It actually encircles both alder shrubs.

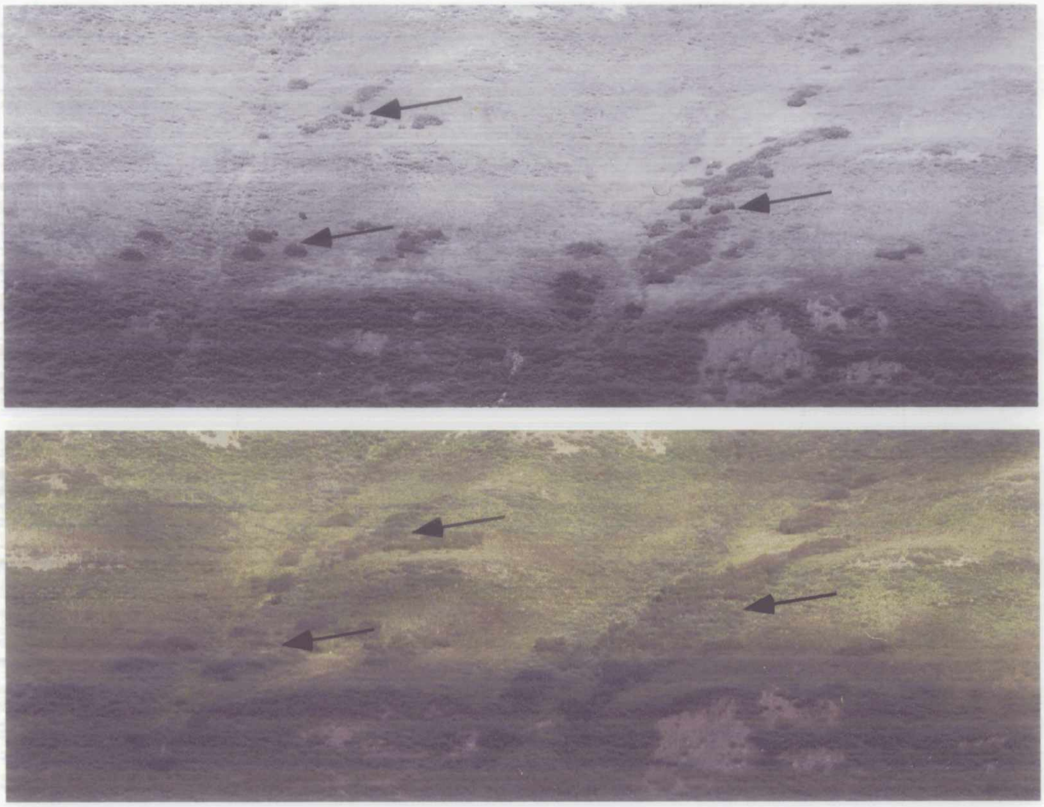

Figure 14. Photos from the Kurupa River (N68° 48.15', W155° 11.42'), taken in 1948 (top) and 2002 (bottom). Notice that willow and birch growth has overwhelmed previously distinct alder forms. Also evident is an increase in alder shrubs.

The Age and Structure of Shrub Assemblages

The analysis would not be complete without mention of what has not changed in these landscapes. Roughly 80% of the individual shrubs identifiable in the old photos are still present in the new photos. This is known because shrubs in the new photographs are usually in the exact locations as shrubs in the old photographs. The increases in percent shrub cover reported in Tables 1 and 2 are typically due to the increase in size of old shrubs, and the addition of new shrubs. For example, if a particular grid cell had 10 shrubs in the old photograph, the grid cell from the new photograph would typically have 8 of the original 10 individuals (all larger now), and 5 new shrubs, for a total of 13 shrubs. If the increase in shrubs was instead achieved by the dying and subsequent replacement of old shrubs (i.e. a higher turnover rate), most shrubs in the new photographs would be in different locations and arrangements than shrubs in the old photographs. This was not the case.

Photo-pairs showing little change in shrub cover over the time interval appear to have the exact same individual shrubs, at the same size, despite the half-century between photos (Figure 15). This is a surprising result suggesting that in limited cases the shrub landscape has been "frozen" in time for 50 years.

In an attempt to age alder shrubs, we cut discs from multiple stems of 34 alder shrubs over the course of this study. We rarely encountered stems that were more than 50 years old, even on shrubs that were clearly present in the old and new photos. We occasionally found alder stems that had over 80 rings (maximum = 99 rings), but that was

Figure 15. 1948 (top) and 2001 (bottom) photos taken near the confluence of the Lupine and Sagavanirktok Rivers (N69° 4.93', W148° 45.72') showing shrubs nearly "frozen" in time. Numbers denote 10 examples where the exact same shrubs exist in the old and new photographs, suggesting that they have been living for at least 50 years. Stems rarely have more than 50 rings, implying that stems are continually dying and being replaced as the individual shrub persists.

unusual. This suggests that stems in a clump experience turnover while the individual shrub persists, an inference to be discussed later.

Treeline

Two of the rivers photographed, the Kugururok River and the John River (the latter not formally included in this analysis), are host to spruce forests at latitudinal tree-line. The photographs from the Kugururok region reveal a pattern of increase for spruce that is very similar to that for alder shrubs on valley slopes: The new photos show that the last half-century has brought substantial infilling of spruce stands, and many of the patches within the tree-line ecotone have expanded into tundra areas (Figure 16). Although tree-line is a mosaic of forested and treeless patches, rather than a discreet line as the name implies, it is evident from the Kugururok River photos that treeline is migrating north in the western part of the study area. Tree-line on the John River, however, in the central part of the study area, is nearly stagnant, with mild infilling.

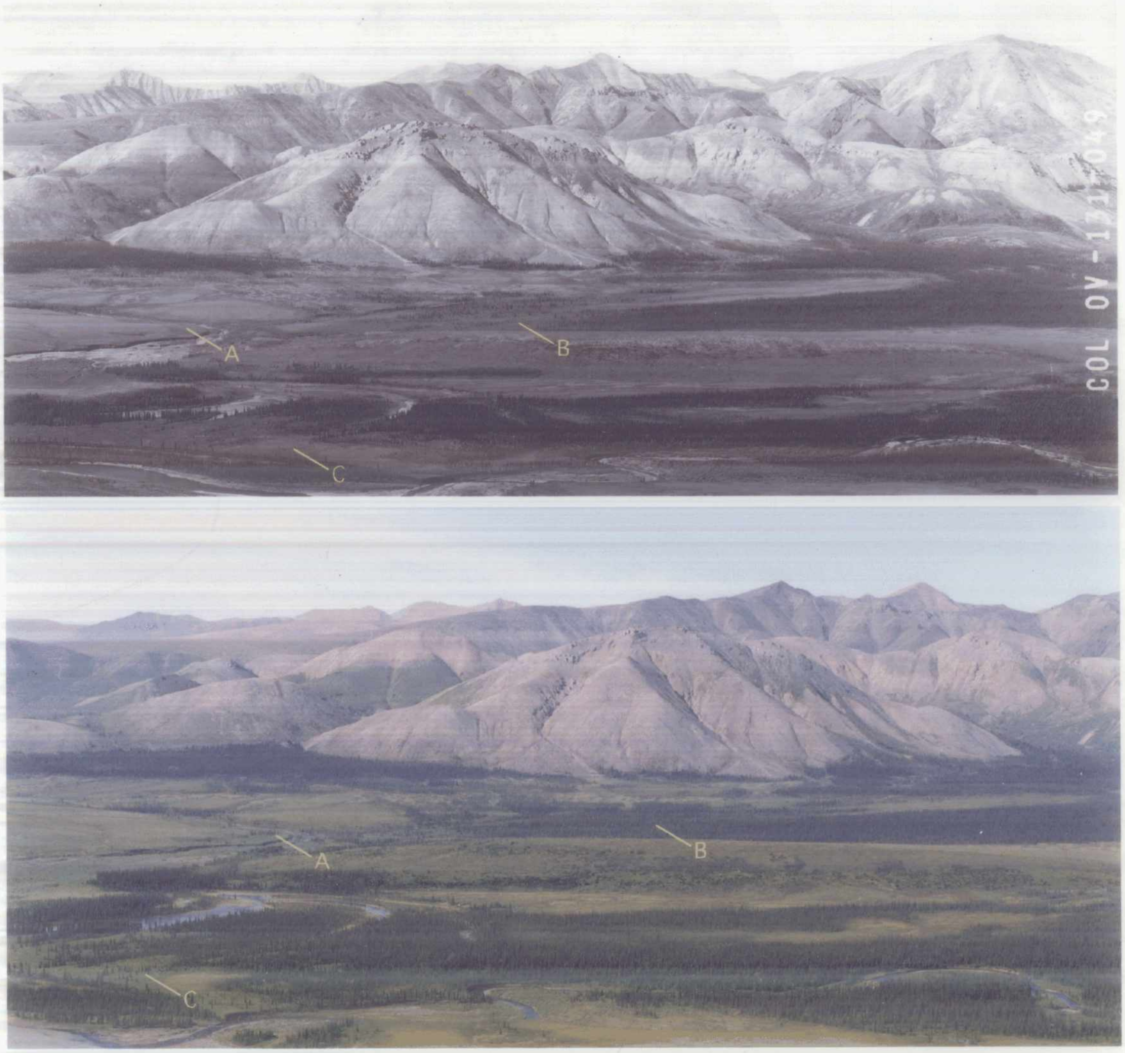

Figure 16. 1949 and 2000 photos from the Kugururok River, a western tributary to the Noatak River (N68° 5.25', W161° 39.42'). Letters denote examples of areas where treeline is expanding.

DISCUSSION

The results from this study show that shrubs on the valley slopes, river terraces, and floodplains are increasing in size and abundance, and colonizing areas where previously there were no large shrubs. NDVI evidence from other studies suggest that small shrubs on interfluvial benchlands are also increasing in size and abundance (Jia et al., 2003). Together, these two sets of data show a general increase in shrubs in northern Alaska (Figure 4). This comprehensive increase in shrubs appears to have been accompanied by stabilization and colonization of floodplains, and migration of treeline (documented herein), painting a picture of an Arctic landscape in transition, one responding to a warming climate.

In principle, the shrub increases documented here are proven only for the photographs we examined. However, given the extensive coverage of the repeat photography, it is reasonable to extend the increase in shrubs throughout similar vegetation zones within the full study area, according to the magnitude of the change documented in particular regions (Table 2). In other words, we can safely extrapolate the increase in shrubs documented in the photos throughout much of the Arctic Slope and northern Brooks Range, according to the magnitude of change in nearby photos. For example, the Tuluga and Siksikpuk River valleys, which lie between the Chandler and Nanushuk Rivers, have probably experienced the same substantial changes in shrub cover as the Chandler and Nanushuk River valleys that bound them.

On the other hand, the repeat photographs have insufficient resolution to tell us about changes on the interfluvial benchlands, where alders and other large shrubs are largely absent. On interfluvial benchlands satellite images, using NDVI, suggest a dramatic increase in small shrubs in northern Alaska over the last two decades (Jia et al., 2003).

Unfortunately, NDVI is difficult to interpret, because it is not clear exactly what attribute of the vegetation it measures. Tucker and Sellers (1986) concluded that "The reflectance data (NDVI) provide indications of the instantaneous biophysical rates associated with plant canopies; gross primary productivity and evapotranspiration, rather than reliable estimates of any state associated with the vegetation, such as leaf area index or biomass." Similarly, Hope, Kimball, and Stow (1993) determined that "Up to 51 per cent of the variance in NDVI was explained by the amount of photosynthetic biomass in the moist tussock and dry heath communities…" Recent studies present a tighter empirical relationship between NDVI and biomass (r^2=0.82), and use it to monitor biomass fluctuations in northern Alaska (Jia et al., 2003). Over the period 1981-2001, an increase in NDVI was recorded that, based on NDVI vs. biomass regression, is equivalent to a 28.1% (±13.3%) increase in biomass. The authors suggest that this increase is driven by shifts in tundra composition toward deciduous shrubs, similar to the shifts documented at Toolik Lake over the same period of time (Chapin et al., 1995). As such, the changes documented using NDVI are consistent with increasing shrubs on the interfluvial benchlands.

The increase in large shrubs documented by the photos in this study is not contributing to the observed increase in NDVI. Using imagery with resolution fine enough to resolve alder patches (Landsat ETM+, 10 m pixels), we determined that alder, and perhaps large willow, saturate the NDVI signal and thus cannot be assessed for temporal changes using this method. So in fact, the studies chronicling recent increases in NDVI complement well the photographic evidence presented here: NDVI studies show increases in low-biomass ecotypes, while the photographs show increases in predominantly high-biomass ecotypes.

The NDVI results document shrub expansion and growth on the interfluvial benchlands. The photos of this study document increasing shrubs on the slopes, terraces, and floodplains of river valleys. Combined they indicate that deciduous shrubs, both large and small, are increasing in all landscape positions throughout the study area and beyond. In other words, a comprehensive shift toward shrubland has been taking place across northern Alaska.

The spatial heterogeneity of the changes observed at treeline confirms recent theory: Even at a treeline limited by temperature, trees exhibit both positive and negative responses to warming, depending on other factors, such as moisture (Lloyd and Fastie 2002; Lloyd et al., 2003). At the southern margin of shrub tundra in the study area, the treeline ecotone exhibited a positive, but heterogeneous response to warming. Treeline in the western Brooks Range (Kugururok River) infilled and extended its 1949 boundary, while treeline in the central Brooks Range (John River) infilled slightly and did not extend its 1948 boundary.

These results – increasing shrubs, consequential fluviomorphological changes, and migrating treeline – portray critical components of a complex system undergoing transition. These results apply throughout the study area, a region comprising 5% of the vegetated global arctic (CAVM Team, 2003).

Changes in vegetation such as those documented here could be occurring throughout the circumpolar region, but if so the extent remains unknown. Large areas of Siberia and northern Canada are experiencing similar warming to that of northern Alaska (Serreze et al., 2000), and they are likely undergoing similar vegetation changes. Anecdotal evidence from northern Canada cite larger willow and alder shrubs as one of a host of vegetation and landscape changes observed in recent decades (Thorpe et al., 2002; Nickels et al., 2002). Other regions of the circumarctic such as eastern Canada and Scandinavia have experienced a lesser degree of warming than northern Alaska (Serreze et al., 2000), so shifts in vegetation in those regions may be muted compared to those in Alaska.

Why is Arctic Vegetation Changing?

The widespread nature and high rate of the change documented here can only be explained by a perturbation operating on a similarly large spatial and short temporal scale. In an ecosystem with limited disturbance, plant succession on a half-century time scale cannot explain widespread vegetation changes. Therefore the perturbation most likely responsible for the increase in shrubs is, directly or indirectly, a regional change in climate.

Tundra manipulation experiments near Toolik Lake, Alaska, located within the study area, show that elevated temperatures promote shrub growth. The elevated temperatures may trigger the increases through changes in nutrient availability, soil moisture, or soil temperature (Chapin et al., 1995). Nonetheless, over a 9-year period starting in the early 1980's, experimentally elevated temperatures increased production of vascular plants (shrubs), but decreased production of nonvascular plants (Chapin et al., 1995).

Some might argue that changes such as those documented here could in fact occur under a stable climate. There is evidence that glacial surfaces and soils in Arctic Alaska evolve over millennia, and that concomitant with this aging are shifts in vegetation (Jorgenson, 1984). The surface and soil evolution is driven by (1) climatic fluctuations and (2) slow processes that include mass wastage, eolian deposition, topographic smoothing, and the development of an organic layer, vegetation, and permafrost (Oswald et al., 2003). These findings tell us that even in an environment free of conventional disturbance (fire, hurricanes, etc.), there should still be slow processes at work that cause soils and vegetation assemblages to change over millenia.

This slow aging process cannot, however, explain the more rapid and synchronous changes observed in this study. Climate fluctuations remain the dominant stimulant for this type of vegetation shift. Oswald et al. (2003) compared the pollen records from lake cores of two proximal Arctic Slope lakes of different ages to determine (1) if differences in substrate caused differing responses to climate changes, and (2) whether landscape-aging or climate changes were responsible for Holocene shifts in vegetation. If long-term soil and geomorphic evolution has indeed been the catalyst for the vegetation change, one would expect the vegetation assemblages from these lakes to evolve asynchronously with each other and asynchronously with shifts in climate. Instead, the two pollen records reveal different but synchronous responses to shifts in climate, indicating that (1) substrate is a factor when considering the vegetation response to climate change, but (2) that climate shifts and associated feedbacks are the main drivers of short-term vegetation shifts in the Arctic (Oswald et al., 2003). The implication for this study is that the 39% increase in shrubs we observed over the past 50 years is the direct result of decadal changes in climate, not succession, disturbance, or evolution of the soil.

Finally, the unchanged "frozen" photos warrant some mention. The frozen shrubs indicate that stability – ecological stability – is possible and present in some locations in the study area, albeit rare. The scarcity of stems over 50 years old suggests that stems composing a shrub are continually dying and being replaced, yet the individual shrub persists, perhaps well over a century. Under a stable climatic regime, shrub abundance could in fact be unchanging as shrub stems die and are replaced. The photo-pairs that show shrubs frozen in time (Figure 15) demonstrate that a virtually unchanging landscape is not only possible, but actually occurring today in a few locations. That observation emphasizes that the increase in shrubs present in 93% of the photos (Type I analysis) is most likely a result of changes in climate.

So what can we speculate about shrub abundance prior to 1950, given the increase we have observed since 1950? While shrubs present in both the old and the new photos have well-developed shrub halos, shrubs new to the landscape since 1950 typically have no halos. That implies that the many shrubs without halos in the old photographs were also new to the landscape. The temperature record (Figure 1) shows increases in temperature in the 1920s and 1930s (immediately preceding the old photography) and 1980s and 1990s (directly preceding the repeat photography). The lack of shrub halos in the old photographs suggests that a similar increase in shrubs to the one documented here occurred between 1900 and 1950. As we look further into the past, we speculate that few large shrubs were present on the landscape 200 years ago, at the end of the Little Ice Age. This makes a case for a general increase in shrubs that started near the end of the Little Ice Age, one that has been enhanced by the two major periods of warming this century.

Implications

This study, in concert with vegetation plot results from Toolik Lake and satellite NDVI records from northern Alaska, documents a pervasive shift toward more and larger shrubs in Arctic Alaska. Such a shift will be accompanied by systematic changes in physical and biological ecosystem parameters ranging from ground temperature to net ecosystem exchange.

With the shift toward deciduous shrubs, we can expect to see, for example, an increase in carbon exchange (Fahnestock et al., 1998) and deeper, more insulative snowpacks (Sturm et al., in press). These are not merely state changes that operate in isolation from the larger system. Rather, these changes are oftentimes amplified (and amplify) through biological and biophysical interactions. Two examples of positive feedback mechanisms that would be triggered by an increase in shrubs are the shrub-snow-microbe feedback cycle (Sturm et al., 2001) and the increase in sensible heat flux resulting from the tundra to shrub tundra conversion.

In the shrub-snow-microbe cycle, the shrub height determines the snow depth, the snow depth controls the winter ground temperature, the ground temperature controls the winter duration of microbial activity, and the amount of microbial activity is directly related to the quantity of nutrients available to the shrub in the spring. Introduce to that cycle the increase in shrubs documented here, and the self-propagating cycle is initiated, further promoting shrub expansion.

A second powerful feedback associated with the shift from tundra to shrub tundra is the change in energy balance. Energy exchange measurements at adjacent tundra and shrub tundra sites on the Seward Peninsula revealed that sensible heat flux was 7.1 W m^{-2} greater at the shrub site than at the tundra site (Beringer et al., submitted). The 7.1 W m^{-2} difference in sensible heat flux between tundra and shrub tundra is much larger per unit area than the forecasted 4.4 W m^{-2} resulting from a doubling of CO_2, emphasizing the severe implications of adding shrubs to the landscape. An increase in shrubs is likely to further increase air temperatures, which will again promote shrub growth (McFadden et al., 1998). Biological feedbacks such as these resulting from the shift from tundra to shrub tundra are likely to further enhance the current warming and vegetation trends.

One consequence of the increasing shrub abundance that is already underway is the stabilization and narrowing of the active floodplains throughout the study area (Figure 12). Thriving shrubs and other vegetation have colonized bars throughout the region, forcing rivers to become more channelized and giving floodplains the appearance of being less active. This restructuring of river morphology will have immediate consequences on the entire hydrologic regime.

CONCLUSION

This study used 202 paired old and new aerial photographs to document an increase in shrubs throughout arctic Alaska. The shift toward a shrubbier arctic, the expansion of treeline, and the fluviomorphological changes presented here depict a terrestrial arctic in transition. In a region of limited anthropogenic and natural disturbance, these shifts are likely driven by contemporaneous warming over the last several decades. Vegetation change on such a large spatial scale, in response to changes in climate, has not been documented elsewhere in the world, but it is likely that similar changes are occurring in regions with similar warming. The change, if it continues, will result in a radical alteration of the tundra ecosystem.

REFERENCES

ACIA, *Impacts of a Warming Arctic: Arctic Climate Impact Assessment.* Cambridge University Press, 2004.

Arendt, A.A., Echelmeyer, K.A., Harrison, W.D., Lingle, C.S., Valentine, V.B. 2002. Rapid Wastage of Alaska Glaciers and Their Contribution to Rising Sea Level. Science **297**: 382-386.

Beringer, J., Chapin, F.S. III, Thompson, C.D., McGuire, A.D. 2004. Surface energy exchanges along a tundra-forest transition and feedbacks to climate. Agricultural and Forest Meteorology, Special boreal forest issue, Amiro Ed. Submitted.

Bockheim, J.G., Walker, D.A., Everett, L.R., Nelson, F.E., Shiklomanov, N.I. 1998. Soils and Cryoturbation in Moist Nonacidic and Acidic Tundra in the Kuparuk River Basin, Arctic Alaska, U.S.A. Arctic and Alpine Research **30-2**: 166-174.

CAVM Team. 2003. Circumpolar Arctic Vegetation Map. Scale 1:7,500,000. Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

Chapin, F.S. III, McGraw, J.B., Shaver, G.R. 1989. Competition causes regular spacing of alder in Alaskan shrub tundra. Oecologia **79**: 412-416.

Chapin, F.S., Shaver, G.R., Giblin, A.E., Nadelhoffer, K.J., Laundre, J.A. 1995. Responses of Arctic Tundra to Experimental and Observed Changes in Climate. Ecology, **76-3**: 694-711.

Chapman, R.M., Detterman, R.L., Mangus, M.D. 1964. Geology of the Killik-Etivluk Rivers Region, Alaska. Geological Survey Professional Paper 303-F.

Fahnestock, J. T., Jones, M. H., Brooks, P. D., Walker, D. A., Welker, J. M. 1998. Winter and early spring CO2 efflux from tundra communities of northern Alaska. Journal of Geophysical Research **103**: 29023-29027.

Fung, I. 1997. A greener north. Nature **386**: 659-660

Gabriel, H.W., Tande, G. F. 1983. A regional approach to fire history in Alaska. BLM-Alaska Technical Report 9.

Hope, A.S., Kimball, J.S., Stow, D.A. 1993. The relationship between tussock tundra spectral reflectance properties and biomass and vegetation composition. Int. J. Remote Sensing **14-10**: 1861-1874

Jia, G.J., Epstein, H.E., Walker, D.A. 2003. Greening of arctic Alaska, 1981-2001. Geophysical Research Letters **30-20**: 2067.

Jorgenson, T., Pullman, E., Shur, Y. 2003. Degradation of Ice Wedges in Northern Alaska in Response to Recent Warmer Temperatures. *SEARCH* meeting, October, 2003.

Kittel, T.G.F., Steffen, W.L., Chapin, F.S.III. 2000. Global and regional modelling of Arctic-boreal vegetation distribution and its sensitivity to altered forcing. Global Change Biology **6-1**: 1-18

Lachenbruch, A.H., Marshall, B.V. 1986. Changing Climate: Geothermal Evidence from Permafrost in the Alaskan Arctic **23**: 689-696.

Lachenbruch, A.H., Sass, J.H., Marshall, B.V., Moses, T.H.Jr. 1982. Permafrost, Heat Flow, and the Geothermal Regime at Prudhoe Bay , Alaska. Journal of Geophysical Research **87-B11**: 9301-9316.

Lloyd, A.H., Fastie, C.L. 2002. Spatial and Temporal Variability in the Growth and Climate Response of Treeline Trees in Alaska. Climatic Change. **52**: 481-509

Lloyd, A.H., Rupp, T.S., Fastie, C.L., Starfield, A.M. 2003. Patterns and dynamics of treeline advance on the Seward Peninsula, Alaska. Journal of Geophysical Research. **108-D2**: Alt 2

Mann, D.H., Peteer, D.M., Reanier, R.E., Kunz, M.L. 2002. Responses of an arctic landscape to Lateglacial and early Holocene climatic changes: the importance of moisture. Quaternary Science Reviews **21**: 997-1021.

McFadden, J.P. Chapin, F.S. III. Hollinger, D.Y. 1998. Subgrid-scale variability in the surface energy balance of arctic tundra. Journal of Geophysical Research. **103-22:** 28,947-28,961.

McFadden, J.P., Eugster, W., Chapin, F.S. III. 2003. A Regional Study of the Controls on Water Vapor and CO_2 Exchange in Arctic Tundra. Ecology **84-10**: 2762-2776.

Moffitt, F.H. 1959. Photogrammetry, 2d Ed. International Textbook Company.

Myneni, R.B., Tucker, C.J., Asrar, G., Keeling, C.D. 1998. Interannual variations in satellite-sensed vegetation index data from 1981 to 1991. Journal of Geophysical Research **103-D6**: 6145-6160.

Oswald, W., Brubaker, L., Anderson, P. 1999. Late Quaternary vegetational history of the Howard Pass area, northwestern Alaska. Canadian Journal Of Botany **77**: 570-581.

Oswald, W., Brubaker, L., Hu, F.S., Kling, G.W. 2003. Holocene pollen records from the central Arctic Foothills, northern Alaska: testing the role of substrate in the response of tundra to climatic change. Ecology **91**: 1034-1048.

Peterson, B.J., Holmes, R.M., McClelland, J.W., Vörösmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., Rahmstorf, S. 2002. Increasing River Discharge to the Arctic Ocean. Science **298**: 2171-2173.

Reed, J.C. 1958. Exploration of Naval Petroleum Reserve No. 4 and Adjacent Areas: Northern Alaska, 1944-53. Geological Survey Professional Paper 301.

Serreze, M.C., Walsh, J.E., Chapin, F.S. III, Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T., Barry, R.G. 2000. Observational evidence of recent change in the northern high-latitude environment. Climatic Change **46**: 159-207.

Smith, P.S., Mertie, J.B., Jr. 1930. Geology and mineral resources of northwestern Alaska: U.S. Geological Survey Bulletin 815.

Sturm, M., Racine, C., Tape, K. 2001. Increasing shrub abundance in the Arctic. Nature **411**: 546-547.

Sturm, M., Schimel, J., Michelson, G., Welker, J., Oberbauer, S., Liston, G.E., Fahnestock, J., Romanovsky, V.E. submitted, 2004. The role of winter biological processes in converting arctic tundra to shrubland. In press.

Tucker, C.J., Sellers, P.J. 1986. Satellite remote sensing of primary production. Int. J. Remote Sensing **7-11**: 1395-1416.

APPENDIX A: Col-Photo Protocol

UNITED STATES PACIFIC FLEET
AIR FORCE
PHOTOGRAPHIC SQUADRON ONE
AERIAL SURVEY DETACHMENT ONE

APO 731-B, Big Delta,
c/o postmaster,
Seattle, Washington,
3 September 1948.

THE TECHNIQUE OF OBTAINING
AERIAL OBLIQUE PHOTOGRAPHS
FOR GEOLOGIC PURPOSES.

When Lieutenant GREGG and I made our first trip to Alaska during January and February of this year to discuss with Commander FISCHER some of the requirements for photography for Petroleum Reserve Number FOUR, one of the subjects high on the agenda was the clarification of instructions for oblique photography of the Colville River and its tributaries.

After talking briefly with Commander FISCHER he referred us to Mr. Stewart FOLK for clarification of the oblique photography specifications, which called for using the K-18 24" camera. The pictures were to be taken with the camera depressed at a 15°angle or lower from the horizon at a scale of from 1 to 2000 to 1 to 3000. The photographs were to have 50% overlap along the line of flight.

This did not appear to be a very difficult requirement and we went on to suggest that if black and white photography would be good for geological study wouldn't color photography be better? Mr. FOLK thought highly enough of this idea to incorporate it in a letter for Commander FISCHER'S signature to the Director of Naval Petroleum Reserves. A short time later a letter of concurrence came through from Commodore GREENMAN and approval from the Chief of Naval Operations soon followed.

So when we returned to Photographic Squadron ONE'S home base at San Diego Lieutenant GREGG commenced immediately to shoot some practice photographs from our twin engine Beechcraft, first in black and white, and then in color. Photographs were taken along selected sections of the California coast to approximate the type of terrain we thought would be encountered in the pet FOUR Area. As soon as we had some worthwhile photographs samples were sent to Commander FISCHER for information and study.

Aerial Oblique photography of river banks for geological survey purposes is not difficult. The following are required;

(a) A versatile airplane capable of operating close to the ground and maneuverable enough to avoid obstructions. It must have good visibility for the pilot so that he can observe the view to be photographed and observe the photographer in the proper position for photography. Good visibility ahead is necessary so that the pilot can pick his course along the river without flying into an obstruction. It must have a large camera hatch or a removable door which will enable aiming the camera out the side of the airplane. The airplane must be equipped with electrical and vacuum connections and it should be large enough for the photographer to be comfortable. Long hours of sitting with a one hundred pound camera in the photographer's lap while he is in a cramped position is not conducive to good photography. A good "inter phone" communication system within the airplane is necessary to enable attaining vital teamwork between pilot and photographer, to identify "targets" and to insure "starting" and "stopping" at the right points. The airplane must be capable of being slowed down because long focal length cameras capable of producing large scale photographs cannot be built to have high shutter speeds. Image movement accentuated by high ground speed will result in fuzzy pictures. The only solution is to slow the airplane down. Flaps are a distinct advantage in this respect. The airplane also should have sufficient range to enable it to remain airborne during the major portion of the photographic day. To have to break off photography to return to base for fuel when the weather is beautiful can be very discouraging. In addition, the aircraft should be capable of operating out of relatively small advanced base fields and should be so well designed that it requires but minor maintenance to remain in flying status at all times. A grounded airplane is worthless for any purpose photography included. The small twin engine Beechcraft is admirably suited to oblique aerial photography for geological survey purposes.

(b) A capable pilot and crew are more necessary to accomplishing a photographic project, all things considered, than any other consideration including the airplane. There is an old saying in the Navy that Iron men and wooden ships will win a battle where wooden men and Iron ships will only go down in defeat. That phrase is true of aerial photography. A capable, agressive pilot assisted by a versatile, hard working crew may be counted to put up a stiff battle against the elements and wide variety of difficulties that an isolated crew in the field will face and usually, unless the odds are entirely against the project the boys will come home with worthwhile prizes in the form of excellent photographs.

(c) The K-18 Camera is excellently adapted to oblique photography of river banks. This camera is well known so I'll not describe it here. The photographer should, however, be so well acquainted with its mechanism that he can repair it with a small kit of tools and a few spare parts in the field. This camera is prone to case drive and magazine difficulties which can render it inoperative unless the photographer can repair it on the spot.

(d) Film, chemicals, paper, and processing equipment are all standard. We used Eastman Kodak Super XX topographic or Aerographic base panchromatic film. Morse developing outfits were used for processing. Packaged chemicals are preferred over the bulk variety because they simplify preparation of solutions. A Sonne continuous-strip printer enables rapid printing of processed negatives for delivery to field survey parties and it is strongly recommended that such a printer be taken up into the field if electricity is available to operate it. Another item of useful equipment is an electric film dryer. Processing of film in the field is strongly recommended because it enables on-the-spot decisions to be made at a time when reflights are possible. Color photography processing is not feasible at an advanced base such as that at Umiat from which our oblique operations with the Beechcraft have been conducted. It is recommended that color film be shipped immediately after exposure to the nearest point where adequate laboratory facilities can be set up, closer temperature control, greater amounts of running water, and more developing equipment are required for color than black and white. Kodacolor film, an Eastman product, was used to obtain the oblique color views being displayed here today. Color photography is roughly five times more expensive (in film costs) than black and white. We developed our Kodacolor film at our main base at Big Delta using the "Line Haul" to fly it to Fairbanks where it was picked up by our own aircraft and returned to Big Delta for processing. The finished film was dropped by parachute from a Photo Liberator to the crew at Umiat so that they could view the film and be judge of the quality of photography being produced and could take steps to improve it if possible.

The technique of flying and taking the prictures is a subject which Lieutenant GREGG will be happy to comment on at length after this presentation. For the purposes of this paper I will outline the procedure briefly. It consists mainly of being able to judge correctly the correct distance out from the river bank and above the terrain.

The "seaman's eye" method is used. The best way to train to develope this seaman's eye is for the pilot to select a known river bank with bluffs which contain easily distinguishable land marks which can be identified later on the photographs. Several runs of passes are made along these bluffs at estimated distances of from 4000 to 6000 feet photographing on each pass. Each time a run is made the pilot and photographer should carefully note the distance as it appears to the eye.

By measuring the known distance between checkpoints on the photographs after processing the pilot can tell exactly how far out the runs were made. In a short time he (and the photographer) soon become proficient at estimating the proper distance.

In the field it sometimes happens that flight lines along the larger rivers will have land marks which fall below the airplane so that they can be "lined up" just as in vertical photography. These will enable the pilot to stay the proper distance out if he flies by reference to them.

The flight lines should be flown in straight-line segments from one bend in the stream to the next.

When the pilot arrives at the area to be photographed a quick observation is made to determine where the flight is to commence and end.

The camera is started one exposure before the first bend comes into the viewfinder and is stopped one exposure beyond the next bend.

The photographer selects a point at the edge of the view finder frame on the edge toward the direction of the line of flight as he "shoots" the first exposure. He follows this into the middle of the viewfinder frame and "shoots" the next exposure, immediately thereafter selecting a new checkpoint on the side and following it into the middle of the frame for another exposure and so on down the flight line to the end of the run. This technique insures that there will be a 50% overlap from picture to picture and that there will be no "gaps".

At the end of a run, the pilot makes a quick observation to select the new flight line and heading and makes a turn left or right which will put him into position for the next run. (Illustration).

Unless the river bank is so situated that the sun never falls on it or prevailing weather prevents photography under conditions of sunshine the river bank is photographed only when the sun is shining on it. Cloud shadows are to be avoided if possible.

The aircraft is flown at a speed of from 80 to 90 knots (indicated) and as smoothly as possible to avoid movement of the camera which would result in "fuzzy" pictures. Cross winds will often require "crabbing" the airplane into the wind in order to fly a straight "track" over the surface of the earth and avoid drifting in closer or being carried out from the bank as the photography progresses.

Maintaining the altitude at from 200 feet to 400 feet over .. terrain has been found suitable over most of the pet FOUR river areas.

Correct exposure is most important, particularly in color photography. Care must be taken to aim the meter in exactly the same direction the camera is to be aimed. If the aircraft is not sufficiently close to the river bank a false light reading is caused by the variation of the background or amount of sky scanned. Care must be taken to compensate for snow patches which occasionally lie along river banks. The high reflectivity of the white snow will cause a higher meter reading and will result in underexposure. To get an accurate light meter reading along a low bank or cliff, it is necessary to fly below the top of the bank at approximately 100 feet out from the bank on a heading that is parallel to the course that will be used on the firing run. The run is made along a section of the bank that is representative of the entire run. The lowest reading that is registered on the meter is used in computing the correct exposure. Along the higher cliffs the light meter run may be flown at a more comfortable distance out from cliffs due to the wider angle the higher cliff presents to the light meter.

APPENDIX B: Description of vegetation determined from field work

code	description of vegetation
1	60% willow, 40% hummocks, some grasses
2	1-m alder, very healthy
3	birch, willow
4	60 cm birch
5	birch
6	mix of birch, willow, alder
7	60 cm willow
8	50 cm birch, leedum
9	2 m-alder, water track
10	inter-tract mix of dense alder, willow, birch
11	birch
12	crewcut, with tussock tundra in between 110 cm high, 170 cm diameter N68° 47.171', W152° 01.935' 2-4 m between shrubs clear cut discs photograph P1 #6801 @15:32
13	tussocks, hummocks, solifluction lobe photograph P2 #6803 @15:36
14	80% 30-50 cm shrubs birch, heavy leedum photograph P3 #684 @15:38
15	3.5 m alder, 2.5 m deep water track
16	birch, dense leedum photograph P4 #6806 @15:42
17	1.6 m crew cut with grasses, no tussocks
18	alder shrub, 270 cm height, 300 cm diameter
19	dryas, in steps, mobile soil
20	apparent bottom of solifluction lobe
21	3 m willow, some dead
22	3 m willow
23	willow, mixed sizes
24	dryas, lupine
25	hummocks, tussocks, limited inter-tussock shrubs
26	flagstone sandstone slag
27	dryas